ANL-19/10

Beamline Design and Beam Diagnostic for Mo-99 Production Facility Utilizing High Power Electron Accelerators

Experimental Operations and Facilities Division

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by
Sergey D. Chemerisov, Roman Gromov, James L. Bailey, and Boni A. Size
Experimental Operations and Facilities Division, Argonne National Laboratory

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BEAMLINE DESIGN AND BEAM DIAGNOSTIC FOR MO-99 PRODUCTION FACILITY UTILIZING HIGH POWER ELECTRON ACCELERATORS

1 INTRODUCTION

NorthStar Medical Isotope, LLC, is planning to produce ^{99}Mo through a γ,n reaction on ^{100}Mo. This pathway for ^{99}Mo production relies on the use of high-power electron accelerators, which are not currently commercially available. IBA Industrial announced in its Summer 2017 newsletter (http://iba-industrial.com/emailing/2017-beamline/index.html) that they have begun working on pulsed Rhodotron features (New Horizon project). This accelerator is capable of producing a high power and high energy electron beam suitable for production via a photonuclear route. Argonne National Laboratory (Argonne), in collaboration with Los Alamos National Laboratory (LANL), provided assistance to NorthStar in technology development. Over the course of several years, we have conducted several demonstrations of the technology that proved the feasibility of photo-nuclear approach [1, 2]. The target, designed by LANL, is composed of a series of ^{99}Mo disks held in a target holder with cooling gaps between the thin disks. Cooling of the target is provided by flowing helium gas under high pressure through the target holder [3, 4].

Handling the high-power beam requires a carefully designed beam transport system because of likely vacuum failure if the beam strikes an uncooled part of the system. This publication summarizes recommendations on the beam transport line equipment, costs, and on the optional components.

2 BEAMLINE REQUIREMENTS

The beamline systems provide a means to deliver the beam to the target without significant beam losses. As discussed in previous publications [5], due to significant variation of the production of the isotope, the highest ^{99}Mo yield per gram of ^{100}Mo is achieved by simultaneously irradiating the target from two opposite sides. Most of the heat deposition in the target occurs from slowing down the electrons, which generates bremsstrahlung photons that, in turn, interact with the ^{100}Mo nucleus to knock out a neutron, thus generating ^{99}Mo. By irradiating from both sides, production of ^{99}Mo is distributed more evenly throughout the target. Because the front window of the target is serving as a barrier between high-pressure helium used for target cooling on one side and a vacuum in the beamline on the other, this window is the most stressed component of the target assembly. By irradiating the target from two sides, one can double the production of the ^{99}Mo isotope while keeping the same thermal load/stress on the target window.

Because the target will be irradiated from two sides by two accelerators, one would want to avoid line-of-sight for the two beams, so that each accelerator does not receive a large radiation dose from the opposing accelerator. This arrangement can be achieved by bending the electron beams with a magnet or a group of magnets. Any accelerator produces a beam with a finite energy spread. When going through the magnet, a non-mono-energetic beam will disperse. To avoid this dispersion, one would want to use an achromatic (non-dispersing) bending magnet system.

Accelerator facility for ^{99}Mo production will generate a very high radiation level inside the accelerator vault during the process. The radiation level in turn drives specific requirements for the construction materials of the installation's components. These components must withstand a high dose of radiation without degradation or decay. Use of any organic material should be avoided. Also, the vacuum chamber, collimators, and beam dump will receive high doses of radiation and thermal loads. These components are supposed to be made from a material that produces the least radioactive isotopes with a long half-life. Instead of the common practice of using non-magnetic stainless steel, it would be preferable to build these components out of aluminum. Aluminum reduces the radiation cooldown time sufficiently, which allows quicker access to the vault for maintenance personnel.

Reasonable beamline requirements are:

- Deliver beam with desired intensity distribution to the target.
- Minimize effects of equipment and beam-parameter fluctuations on beam placement on the target.
- Allow for an efficient radiation shielding placement.
- Contain necessary diagnostics components for commissioning and tuning.
- Contain sufficient diagnostics components for beam monitoring during irradiation.
- Protect (disable beam) target and beamline components in case of power supplies or vacuum failure.
- Achieve reliable operations and long lifetime.
- Protect accelerator components and personnel from pressurized target cooling gas in case of target window failure.
- Prevent accidental placement of electron beam on un-cooled parts of the target and beamline.
- Provide appropriate vacuum in the beam pipes and accelerator.

Figures 1–3 depict three beamline configurations discussed previously in several publications [6–8]. Figure 1 represents the beamline with two small angle bending magnets and a single quadrupole magnet, which compose the simple achromat bending system. While this configuration is relatively simple in design and operation, the small angle between the incoming

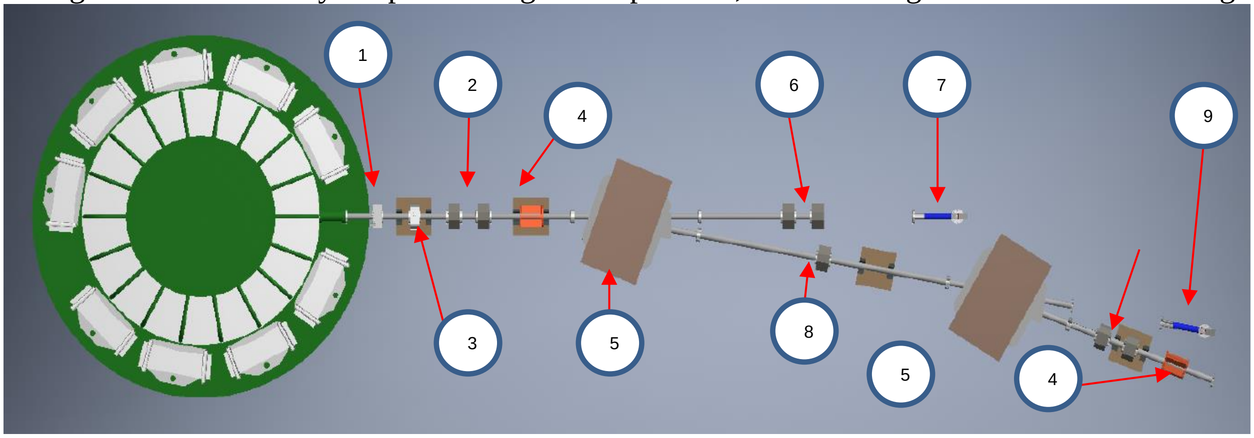

FIGURE 1 Beamline Configurations with "Small Angle" Achromat. Beamline elements are: 1- vacuum gate valve, 2- quadrupole magnets pair, 3- fast acting gate valve, 4- dipole correctors, 5- small angle bending magnet, 6- beam diagnostic optics, 7- beam stop for beam diagnostic, 8- single quadrupole magnet, 9- magnetic spectrometer/beam stop.

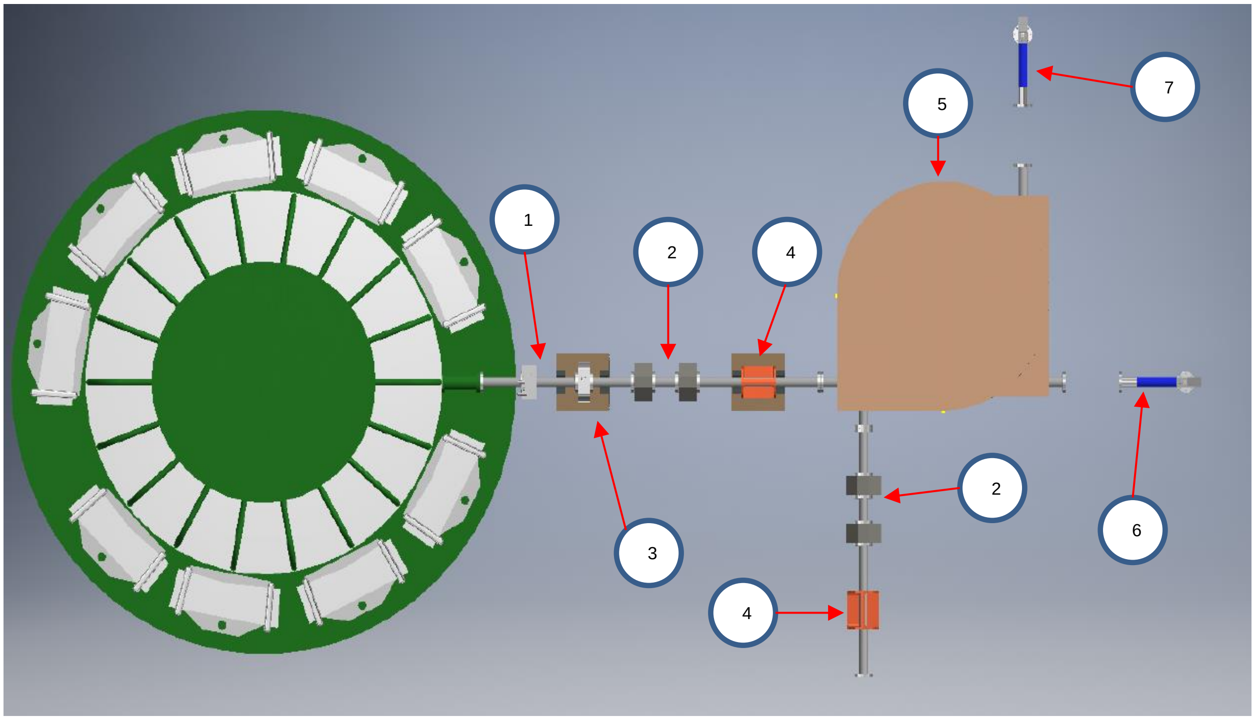

FIGURE 2 Beamline Configurations with 270-Degree Achromat. Beamline elements are: 1- vacuum gate valve, 2- quadrupole magnets pair, 3- fast acting gate valve, 4- dipole correctors, 5- 270-degree achromat magnet, 6- beam stop for beam diagnostic, 7- magnetic spectrometer/beam stop.

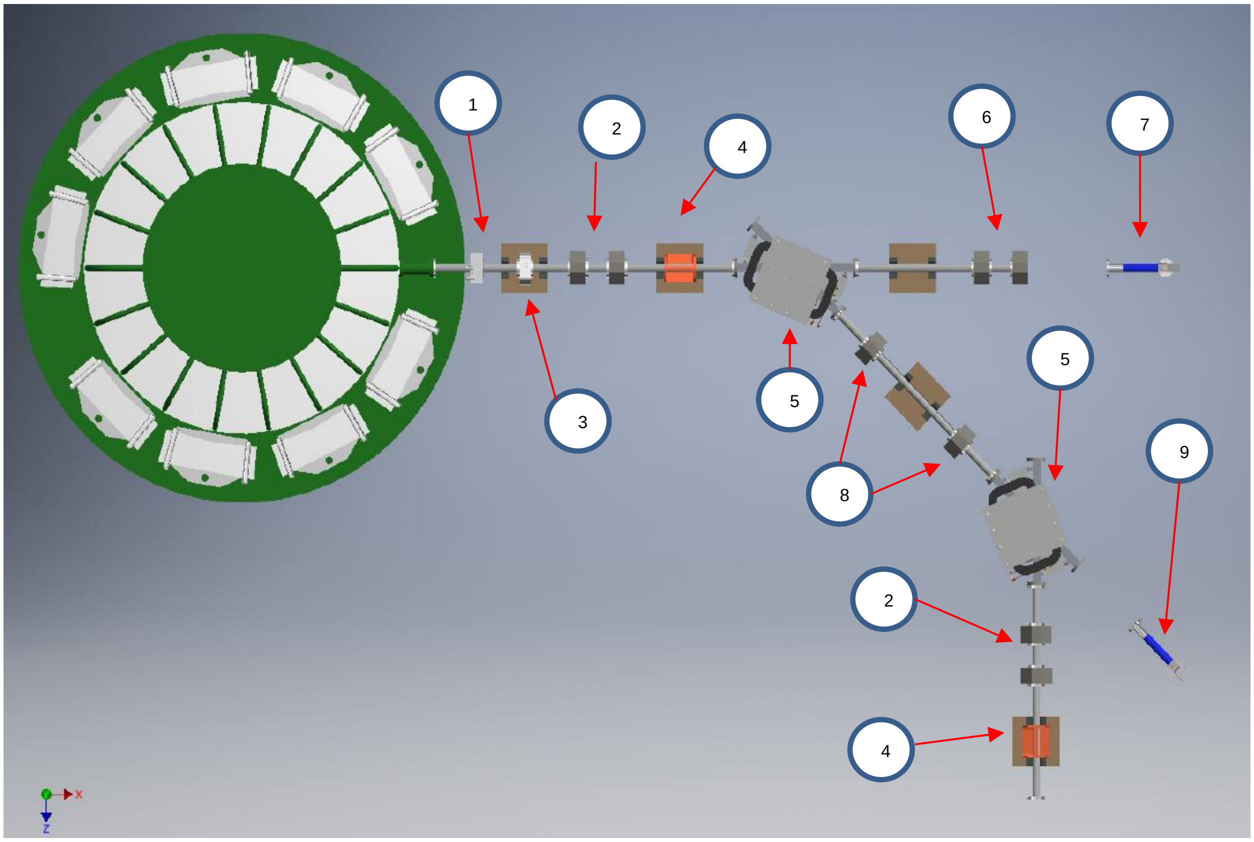

FIGURE 3 Beamline Configurations with 90-Degree Achromat. Beamline elements are: 1- vacuum gate valve, 2- quadrupole magnets pair, 3- fast acting gate valve, 4- dipole correctors, 5- small angle bending magnet, 6- beam diagnostic optics, 7- beam stop for beam diagnostic, 8- single quadrupole magnet, 9- magnetic spectrometer/beam stop.

and outgoing beams will lead to an increased radiation field from the target or will require additional shielding to protect accelerator components. Figure 2 represents the beamline with two 45 degree bending magnets and two quadrupoles forming the 90-degree bend achromat with larger beam energy acceptance. This configuration also places the accelerator at 90 degrees relative to the direction of the beam striking the target, thus reducing the radiation field near the accelerator. The beamline depicted in Figure 3 achieves the same 90-degree bend by rotating the electron beam 270 degrees. The 270-degree dipole magnet in this case will require a gradient of magnetic field to provide achromatic conditions for beam transport.

3 BEAMLINE COMPONENTS

3.1 Vacuum System

For efficient beam transport inside the accelerator and to the target, a high vacuum must be maintained. To prevent electrical discharge and cathode degradation, a vacuum inside the accelerator must be maintained to better than $1x10^{-7}$ torr. This level of vacuum is usually achieved by ion pumps. The beamline vacuum must be maintained at a level of $1x10^{-6}$ torr. The choice of pumps for the beam transfer line is based on gas load. Gas load will mostly come from degassing of the beamline components when they interact with the beam, as well as gases from the target housing that are bombarded with the high power electron beam.

In our experience, the beamline vacuum can be kept below $1x10^{-7}$ torr with properly sized and appropriately placed turbomolecular pumps. We would recommend three turbomolecular pumps, one for each straight beamline section for a two-magnet system achromat; or one for each straight section and one for the 270-degree magnet chamber with single magnet achromat system. During irradiation, the pressure in the beamlines will increase to $1x10^{-6}$ torr in most parts of the beamline and $1x10^{-5}$ torr near the target. The lifetime of an ion pump operating at $1x10^{-5}$ torr pressure is six months to one year, and an equivalently performing ion pump is several times larger than a turbo pump. Based on these observations, the vacuum pump for the beamline should be a turbomolecular pump backed by a rotary-vane fore-vacuum pump. This arrangement has a wide working pressure range, high pumping speed, and long maintenance intervals.

3.2 Beam Transport Magnet System

The line-of-sight problem with the two accelerators mentioned earlier would activate accelerator components and cause premature failure. To avoid this situation, one would bend the beam so that the bremsstrahlung photons would not hit the opposing accelerator. Because any accelerator will produce an electron beam with some energy spread, as well as with instability in the beam energy, the bend magnet systems must deliver a beam with different energies to the same position on the target. This problem is even more pronounced in the production facility design because of the large distance between the bending magnet and the target due to shielding requirements. Multiple configurations of the bending magnet systems can overcome these complications. Any of the three beamline designs depicted in Figures 1, 2, and 3 provide appropriate beam position stability, while the bending magnet system utilizing two dipoles and two quadrupoles (Figure 3) shows better acceptance for the electron beams with wide energy spreads.

To control the size and shape of the electron beam, a set of optical elements must be employed in the beam transport system. So far, all experimental and design target work has been based on a Gaussian beam-intensity distribution, which naturally occurs in charged particle beams. The only important parameter that needs to be controlled is the beam size on the target. For the proposed production facility configuration, the desired beam size is 12 mm full width half maximum (FWHM) at the entrance window to the 29 mm diameter target.

Argonne has built and tested the 90° achromatic bend, which consists of two 45° bending magnets to turn the electron beam and quadrupole lenses with a magnetic field gradient to compensate for beam dispersion due to energy spread [10]. The classical two-bend achromatic approach uses one quadrupole lens between the two bends. Using two quadrupole lenses helps to increase acceptable beam energy spread. Computer simulations for this bend system were performed for a beam with emittance of 500 mm-mrad and 1500 mm-mrad, which are within reasonable expectation for an electron linear accelerator similar to the one used in testing the beamline prototype at Argonne. The simulations also assumed a relatively narrow energy spread of dE=±2.5%. Simulations also were conducted at 100 mm-mrad emittance and 10% energy spread. The results of those simulations are presented in Figures 4 and 5.

The beam transport through a 90° bend for a large beam energy spread was simulated using the particle tracking code Parmela. An input beam with a normalized emittance of 1000 mm-mrad and a distribution beam energy half-width of 10% was used. With these conditions, the beam envelope in Figure 5 was calculated.

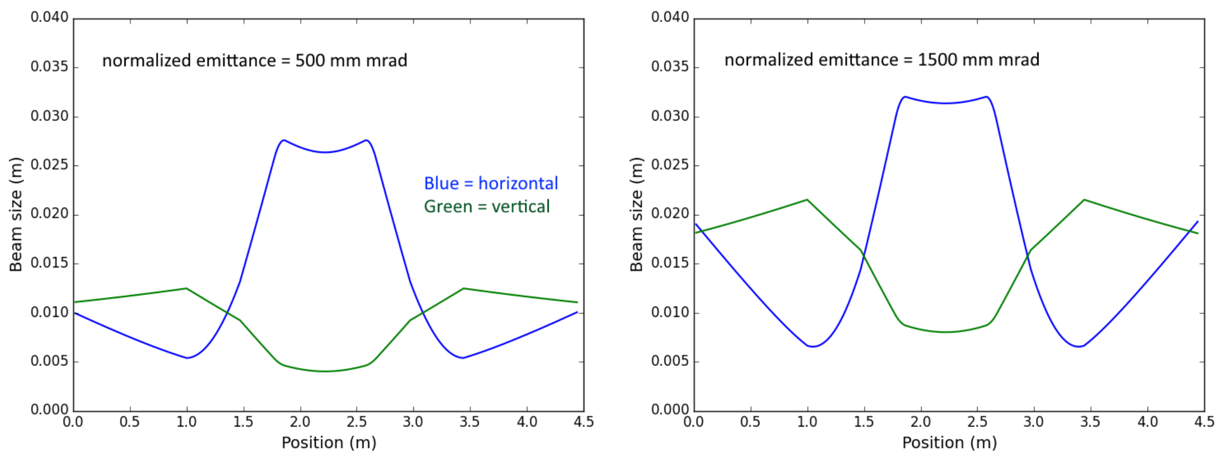

FIGURE 4 Beam Envelopes at 90° Bend for 2.5% Energy Spread for Two Normalized Beam Emittances: 500 and 1500 mm-mrad.

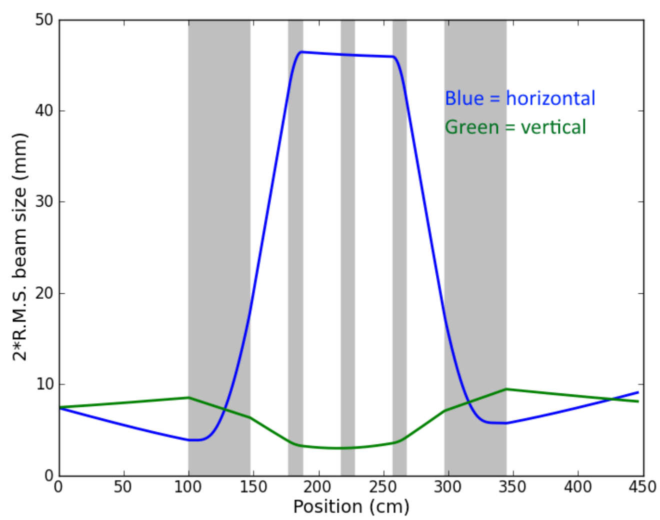

FIGURE 5 Beam Envelope at 90° Bend for Beam Transport with 10% of Energy Spread and 100 mm-mrad Emittance.

A beam envelope simulation was performed to estimate the minimal aperture of the vacuum chamber. Based on the above results, the minimum horizontal aperture of the vacuum chamber should be at least 35 mm for a beam energy spread of ±2.5% and at least 47 mm for a beam energy spread of ±10%. In practice, the energy spread of the beam that is used is always smaller than ±10%, so the limitation for the horizontal aperture of vacuum chamber should not be a problem.

To test a 90° beamline prototype, the bending magnets were designed to have a rectangular shape. The vacuum chamber has a straight line for through-pass of electrons, a 60° bend, and an opposite flange for an optical port. Control of the beam transverse profile is based on an optical transmitted radiation (OTR) camera, which has been successful in beam size/position monitoring [4].

The experimental set-up installed at the Low Energy Accelerator Facility (LEAF) at Argonne is shown in Figure 6. At the exit of the accelerator, a quadrupole doublet focuses the beam into the entrance of the bend. The 90° bend prototype was assembled from two 45° bends and two quadrupole lenses with apertures of 5 cm. The 45° bends are water-cooled with water interlocked power supplies. To test the performance of the beam transport system, an aluminum window was installed at the end of the vacuum chamber (~1 m after the second bend magnet). The beam was placed onto a water-cooled aluminum plate and imaged by the OTR camera. The beam transverse profile and position were acquired from the OTR image of the beam.

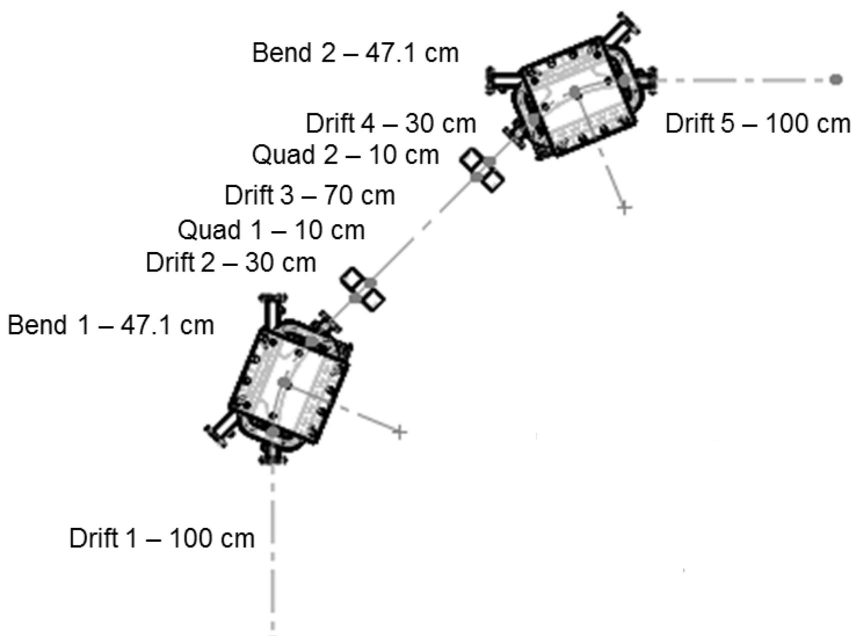

FIGURE 6 Drawings of the Achromatic Bend.

The beam energy profile was measured by a spectrometer installed in front of the 90° bend prototype. This spectrometer has the limitation of the top energy measurements being 40 MeV; therefore, all experimental runs and measurements were performed in the energy range of 33–40 MeV. An accelerated beam has close to a round shape with transverse size of about 5 x 5 mm FWHM (Figure 6). The exit energy of the electron beam was controlled by changing the amplitude of the injector pulse current (beam loading), which was in the range of 0.5 A–0.8 A.

The dynamical stability of an electron beam on the reference trajectory was measured. The accelerator was initially tuned up to a fixed beam energy of 36.5 MeV. After that, the beam energy was increased and decreased by changing the injector pulse amplitude while monitoring the total beam current and its displacement from the initial position. The exact beam position was measured by the OTR camera, which has a resolution of 0.117 mm per pixel. The total beam current was measured with a water-cooled aluminum beam stop, installed after the output window. Experimental results are presented in Figure 7. The beam displacement is less than 1 mm for an energy deviation of ±1.5 MeV (±4.2%). Beam intensity loss is less than 18% for an energy offset of ±1.0 MeV (±2.7%), and less than 8% with energy offset of ±0.5 MeV (±1.4%).

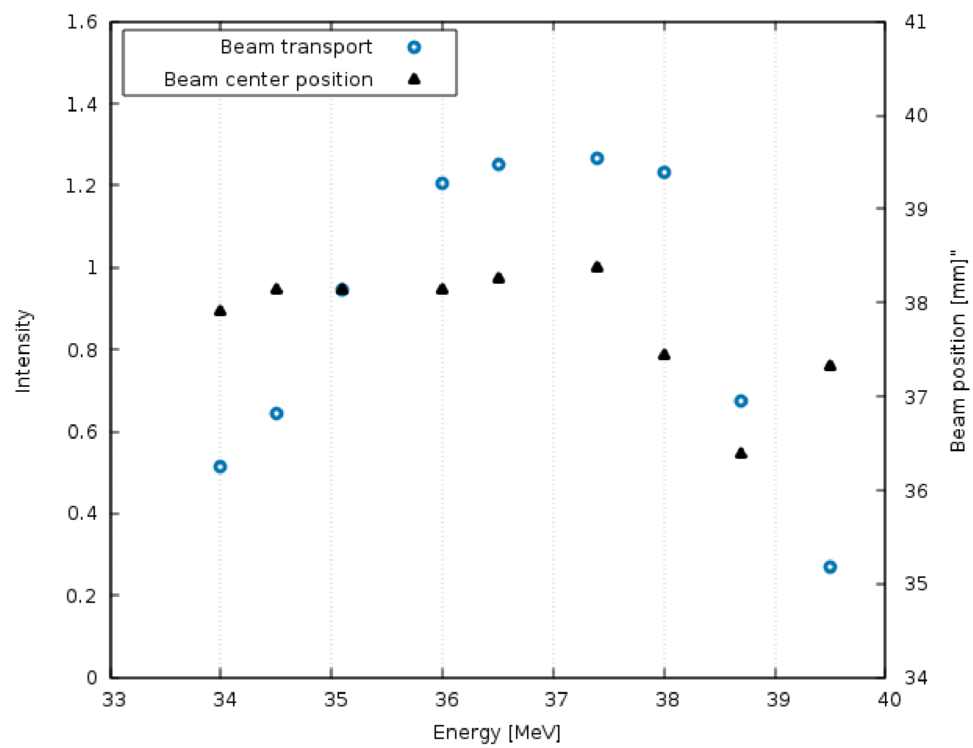

FIGURE 7 Variation of Beam Horizontal Position and Transport Coefficient versus Energy Deviation.

3.3 Beam Diagnostics

A beamline equipped with a sufficient number of beam diagnostic tools is critical to achieve high reliability of accelerator operations for a Mo-99 production facility. Diagnostic tools can be divided into destructive and non-destructive classes. For destructive beam diagnostics, the whole or part of the beam is intercepted to produce an electrical or optical signal proportional to the current density. Most destructive diagnostic components can be used only during the tune-up operation, because they disturb the beam delivery to the target. The only notable exception is an OTR monitoring system, which uses light emitted by high-energy electrons impacting a target window. Because the window separates the vacuum and coolant sides of the target, it is in place during normal operation. While OTR cameras can be used for the beam imaging on the target window, they have a limitation on repetition rate and provide monitoring of only a single-point position of the beam. For tune-up and high repetition rate operation, OTR cameras should be supplemented by other non-destructive methods for beam position monitoring capable of operation at the full repetition rate of the accelerator.

Beam position monitors (BPMs) are widely used for non-destructive diagnostics by nearly all accelerators in the world. They measure relative position of the center of mass of the beam and can be used to measure the total beam current and longitudinal bunch shape. The control electronics measure the voltage induced by the electric field of the charged particle beam on an insulated metal plate. To determine the beam position, four plates are installed 90 degrees apart at the beam pipe. The displacement is measured directly by calculation of

$$dX = Kx \bullet \log(U1/U2)$$

where dX is the beam displacement from the center of the BPM, Kx is a multiplication factor that depends on BPM geometry, and U1 and U2 are the signal amplitudes from the opposite pairs of electrodes. Signals from separate channels are processed simultaneously by electronics synchronized with the beam pulse. Each channel has an input band-pass filter, followed by an amplification chain.

A system of three BPMs was installed and tested at the LEAF at Argonne with assistance from LANL [10]. The system consists of pickups, control electronics, and signal cables. The four-plated pickup is incorporated into a standard 4.5 in. CF flange (Figure 8). These pickups were designed and provided for our tests by LANL. Each pickup is installed in a 45°-rotated position (Figure 9). In this setup, the beam displacement is calculated according to the following equations:

$$dX = Kx \bullet (\log(U1/U2) - \log(U3/U4)) \cos(45°)$$

$$dY = Ky \bullet (\log(U1/U2) + \log(U3/U4)) \sin(45°)$$

The signal cable is a radio frequency (RF) cable with low damping in the RF frequency range. Since the signals on each channel are processed independently, but triggered synchronously, the electrical length of the RF cables must be equal within ±20 cm (±1 ns delay).

FIGURE 8 Pickup with Standard 4.5-in. CF Flanges Provided by LANL and Installed and Tested at Argonne Linac.

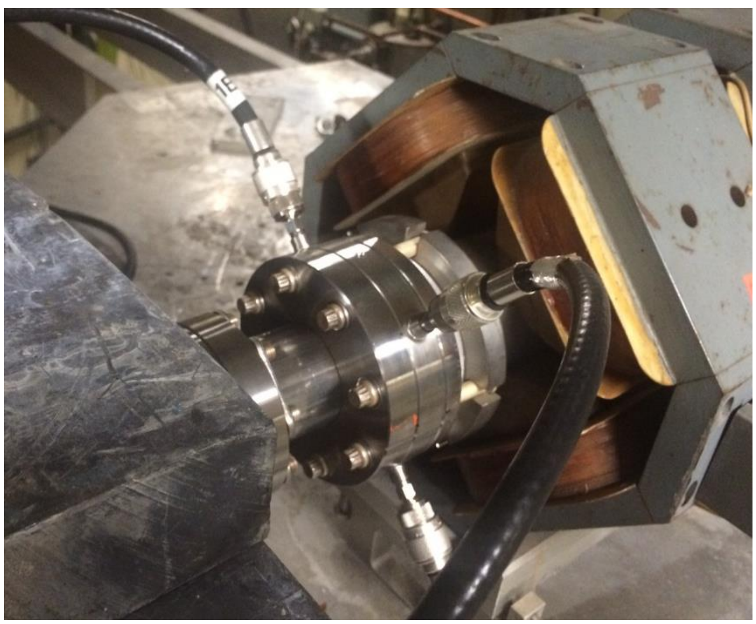

FIGURE 9 BPM Pickup Installed at the Beamline and Connected with Signal Cables to the Controlled Electronic.

The BPM electronic module S-BPM-111.3.2 was designed and manufactured by Bergoz Instrumentation (http://www.bergoz.com). The module reads the raw signal from the BPM sensor, processes it, and sets up output voltage, which is proportional to the beam deviation from the central point. The output signal is processed by the analog-to-digital convertor and translates to the operator’s control screen. The amplitude of the signal was about 0.5 V per 6 mm of beam displacement from the center of the pickup. Noise levels of the processed signal did not exceed 0.005 V.

As mentioned before, destructive beam diagnostics can be used during tune-up and commissioning of the accelerator. This diagnostic component can be either permanently installed or can be mounted on actuators that can insert the diagnostics into the beam pass when necessary. Example of a permanently installed destructive beam diagnostic tool is the beam stop at the zero-degree or 45-degree beamline position. A zero-degree position can be used for initial beam tune-up to measure beam profile and current at nominal beam power, while a 45-degree position can be used for energy spectrum measurements. In high energy accelerators, where the average current is small, OTR (Optical Transition Radiation) screens (insertion devices) are typically used for beam visualization. This solution would be impossible for a production accelerator because of its very high power. The only possibility for beam visualization in a production facility accelerator setting is to image the beam on the target or use a high-power beam dump. A high-power beam dump capable of imaging a full power beam was designed at Argonne and is described in [9].

4 COST ESTIMATES

Table 1 shows the cost breakdown for beamline components for a production facility beamline design. Examples of systems similar to those installed and tested at Argonne are used when possible, and other costs are generated from quotes or prior similar purchase experience. Estimates are rounded up to thousands of dollars in the table and the entire system adds up to $372,000.

For a large facility with multiple accelerator systems, the cost for each item will likely be reduced.

5 BEAMLINE PROTECTION INTERLOCKS

The beam transport line is used to transport an accelerated beam from the accelerating structures to the target face. Because the ultimate average power of the beam is very high—120 kW—the coefficient of transportation should play the key role in machine performance. Losing the full or a fraction of the beam due to multifunction, misalignment, or deviation in performance of beamline elements may result in a deposition of high power to the vacuum chamber. The line may overheat and even damage the vacuum inside the channel. Therefore, reliable interlock protection is required for the new beamline production facility system.

TABLE 1 Cost Estimates for Complete Beam Transport System

Components	Count	Cost per Unit	Additional Information	Support System	Support System Cost	Total Cost
Magnets system						
Quadrupole	8	$3,000	Radiabeam	Power supplies and cables	$2,000	$40,000
Dipole correctors	4	$1,000	Radiabeam	Powers supplies and cables	$1,000	$8,000
Dipoles	2	$19,000	Danfysik	Power supplies and cables	$5,000	$48,000
Vacuum system						
Beamline pipe (m)	20	$500	MDC	Beamline supports, hardware	$500	$20,000
Bend chambers	2	$10,000	MDC, Kurt Lesker	Chamber supports, hardware	$500	$21,000
Bellows	6	$500	MDC, Kurt Lesker	Hardware	$100	$3,600
Turbo pumps	3	$10,000	Leybold	Controller, support and cables	$5,000	$45,000
Fore pumps	3	$3,000	Leybold	Connection hardware	$300	$9,900
Ion gauge	3	$500	Agilent	Controllers, cables	$500	$3,000
Gate valve	1	$3,000	MDC, VAT valve	Hardware, support	$500	$3,500
Beam diagnostics						
OTR camera	3	$1,000	Basler	Hardware, POE, cables	$1,000	$6,000
Lens	3	$1,000	Nikon			$3,000
Mirrors	3	$500	Edmund	Hardware	$500	$3,000
Viewport	1	$1,000	MDC			$1,000
IR camera	1	$24,000	FLIR	Software	$3,000	$27,000
Lens	1	$12,000	FLIR			$12,000
Mirrors	2	$500	Edmund	Hardware	$500	$2,000
Viewport	1	$2,000	Custom			$2,000
High power beam stop	2	$10,000	Custom	Support, hardware	$1,000	$22,000
BPM	3	$1,000	MDC	Electronics	$6,000	$21,000
FCT	3	$2,000	Bergoz	Electronics, computer	$2,000	$12,000
Machine protection						
High power collimator	1	$10,000	Custom	Support, hardware, cables	$1,000	$ 11,000
"Fast" collimators	2	$2,000	Custom	Support, hardware, cables	$1,000	$6,000
Fast acting gate valve	1	$6,000	VAT valve	Controller, cables, sensor	$10,000	$ 16,000
Image analysis	1	$5,000	Custom	Software	$5,000	$ 10,000
Interlock system	1	$15,000	Custom	Cables	$1,000	$ 16,000
Infrastructure						
Support tables	5	$5,000	Custom			$25,000
Water supply/cooling	1	$10,000	Custom			$10,000
Total cost						$372,000

5.1 Strategy of Beamline Protection

An interlock system for a production facility should provide safe and stable performance during long production runs. The most crucial issue for the system is partial or complete loss of the beam during full power operations. Such a loss may lead to damage of beamline elements (vacuum chamber, gate valves, etc.) and lead to excessive activation of equipment beyond the target shielding. There are a few possible reasons for losing the beam during transport to the target face: breaking or malfunctioning of power supplies, or local heating of the magnetic elements, which may lead to fluctuation of the currents or detuning of the RF system. Some of these malfunctions may require immediate termination of the irradiation; for instance, in the case of a broken power supply. Some failures may require the attention of responsible personnel; for instance, in the case of target temperature nearing the safe limit. Therefore, two levels of interlock protection are required for the system: “warning” level and “alarm” level. A warning will trigger an alarm for the accelerator operator on duty to correct possible abnormal behavior of the machine. The accelerator operator will make a decision as to what to do: continue the irradiation, try to tune the machine performance, stop the irradiation, or other action. An alarm level will immediate stop the machine and inform the accelerator operator of the nature of the failure.

5.2 Hardware Interlock

The hardware interlock is used to prevent damage of the beam transport line in case a serious problem occurs that causes immediate damage to the machine in the next pulse. For instance, if, for some reason, the bending magnet power supply is broken or tripped, the beam on the next pulse will strike the vacuum chamber wall. The acting time of the hardware interlock should be below 1 ms, which is enough to prevent the next pulse and prevent irreversible damage.

The prototype of the hardware interlock was designed and tested at the Argonne Linac. The first one is used to detect arcs in accelerating structures. Arcing may be crucial for reliable performance of an RF system. First, the arc produces a local area cloud of degassed components and metal vapor. Next. the RF pulse will produce an instant RF breakdown at this area and arc, which can damage the surface of the cavity. The arc leads to degradation of the surface and, eventually, to irreversible damage of the cavity. Therefore, the RF power must be interrupted immediately after an arc occurs. The hardware interlock has been tested and is being used successfully to prevent sequential RF breakdowns. In this system, the measured signal from RF directional couplers goes to the input of a box current integrator, triggered by the master trigger. Integrated voltage goes to a comparator. The second input of the comparator is tuned up manually, depending on the desired triggered value. When a signal from the comparator exceeds the preset level of operation, the RF system is suspended.

A second hardware interlock system has two comparators and two tripping levels: upper and lower. This approach is for use with a pre-target power collimator [9]. It measures the cut-off halo of the beam and uses this signal to interrupt accelerator operation if the value is outside a desired window, thereby protecting the target window and the beamline from excessive power deposition.

This prototype has an input that goes to the box current integrator, triggered by the master trigger. Output voltage goes to two comparators. The levels for those comparators are tuned up manually by two potentiometers. One comparator is for a lower level signal, and another comparator is for an upper level. This system can be used only after putting the accelerator into "standard" operational conditions.

5.3 Software Interlock

A software interlock usually has a sufficiently longer response time. This response time depends on factors such as processor load, volume of data transfer, or system configuration. The characteristic times of triggering for a software interlock may be from milliseconds up to tens of milliseconds. This time is often enough to produce several pulses of the high intensity beam. But this is acceptable, for instance, in case when beam is starting to deposit energy on the water-cooled collimator, or the beam becomes defocused due to malfunction of the quadrupole power supply. In the last case, the defocused beam cannot cause damage in a few pulses because of the low power density of the defocused beam.

The concept of a software interlock was developed and tested at the Argonne LEAF Linac. Now, the software interlock is part of the Linac's control system. The system is based on the Argonne Experimental Physics and Industrial Control System (EPICS) [6]. Each monitored process variable (PV)-channel has two levels of alarms, which can be armed independently. One is used as a "warning" level. The warning produces an alarm signal for the Linac operator if the controlled value goes out of normal operating parameters. After receiving the warning signal, the Linac operator makes a decision to adjust the parameter, stop the irradiation, or other action. The time necessary for reaction on a warning level is usually long—from seconds up to minutes.

The second level is an "alarm." The alarm level applies if some measurement parameters go outside the safe level. In the case of alarm, the software will activate the interlock relay, which prevents triggering impulses to the RF power system and stops the generation of a high-power beam. The time reaction may vary from a few milliseconds up to tens of milliseconds. During this time, the accelerator can produce up to 1% of the average power, which is not crucial if the beam deposits energy only on water-cooled components.

The software interlock system is designed to set up the tripping points and arms any of the interlock levels for all critical, measured channels: beam transport line power supplies, injector current, vacuum level, beam x- and y- FWHM at the target window, beam position at the target window, and so forth. See Figure 10.

A very important element of the software interlock is the OTR-camera signal from the entrance window of the target. This camera has a limited repetition rate up to 100 Hz. It grabs the image, processes it by using GSL fast library code [7], and sends the data to the processing algorithm. See Figure 11.

Another area of extreme importance for accelerator protection is providing vacuum protection from a target window failure. The molybdenum target is cooled by a flow of high-pressure helium gas. The target window is exposed to high mechanical and thermal stresses, and its failure would result in an in-rush of high-pressure helium gas to the beamline and accelerator. To protect the accelerator, the beamline must be equipped with a fast-acting gate valve system. Such a system is installed and operational at Argonne. Recently, we have conducted a series of tests to quantify the effectiveness of such a system. The results of the tests are reported in [4].

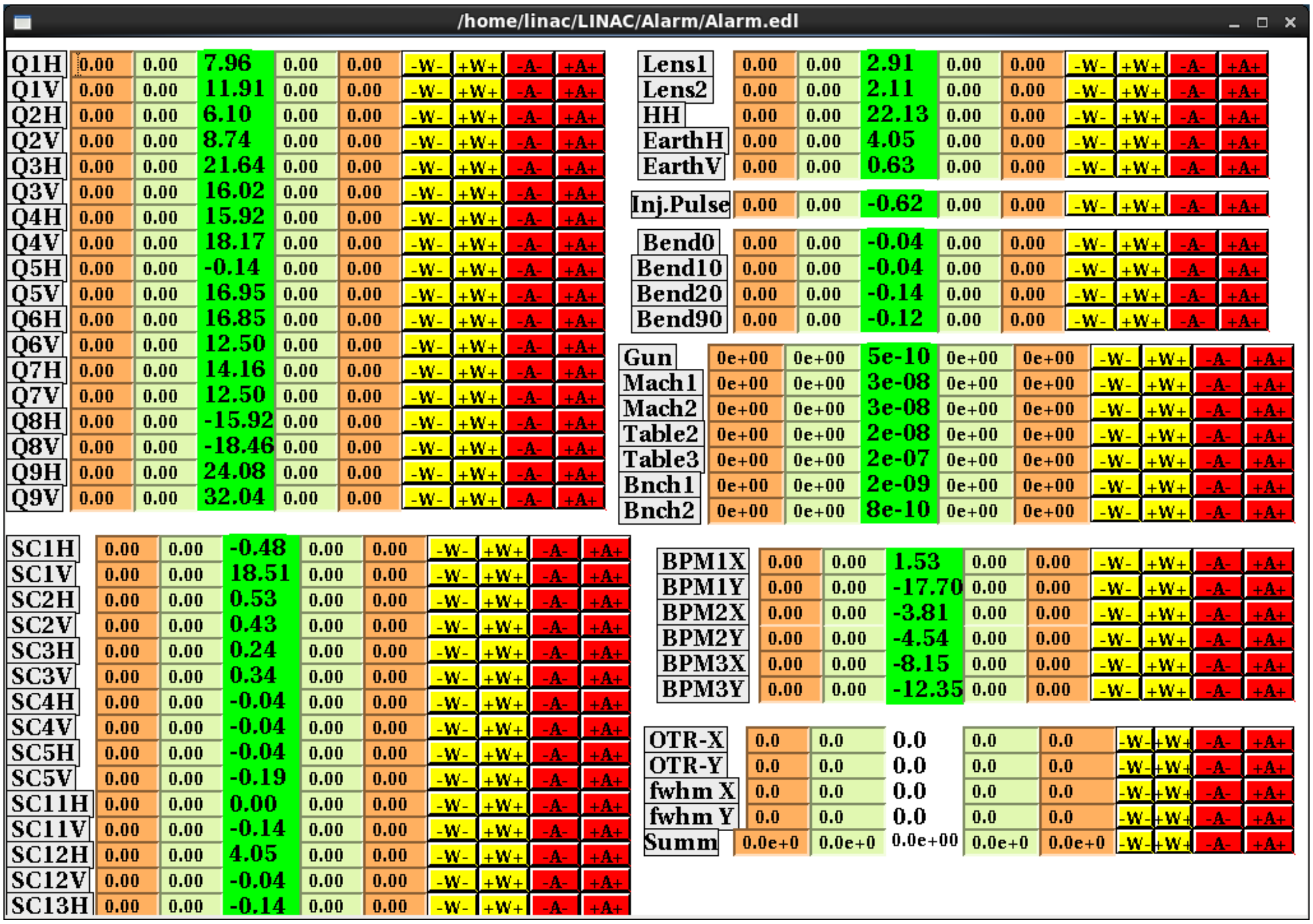

FIGURE 10 Client GUI for Setting Up Software Interlock Levels and Values.

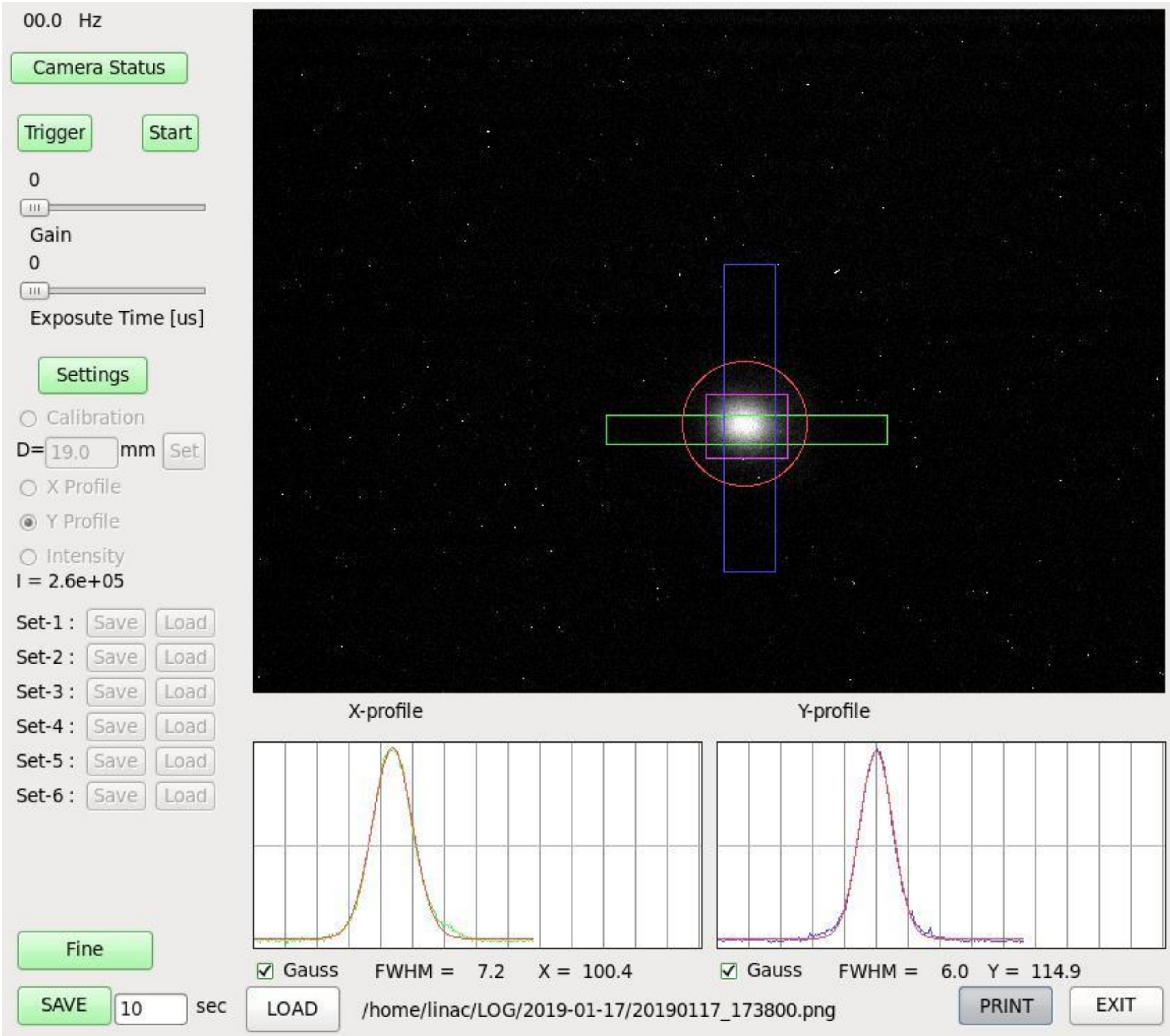

FIGURE 11 OTR-Camera Image for Beam Parameters Calculation at the Target Window (Post-Experimental Image Processing).

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Experimental Operations and Facilities Division
Argonne National Laboratory
9700 South Cass Avenue, Bldg. 205
Lemont, IL 60439-4854

www.anl.gov